SYSTEM STUDY FOR A POSSIBLE ATLAS RADIATION OPTION

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ABSTRACT

In this paper, we analyze design options for implementing a fuse and a plasma opening switch on the Atlas generator for applications involving radiation production from a Z pinch. Transmission line circuit models of Atlas have been developed that include physics-based electrical models for the opening switches and Z pinch. The kinetic energy of the Atlas imploding Z pinch is calculated for the various design options. The results suggest that the fuse option is inefficient. The plasma opening switch option shows promise, but has scaling issues. This work points out the importance of appropriate values for current limiting resistors when altering the Atlas circuit. These analyses are not complete, but are a starting point from which these design options can be pursued further.

INTRODUCTION

Atlas is a pulsed power generator being designed and built by the Los Alamos National Laboratory (LANL).[1] It will be used as a driver for hydrodynamic experiments in support of weapons-physics investigations for the Science Based Stockpile Stewardship Program.[2] Atlas is also being evaluated for its applicability to produce soft x-rays for weapons physics related radiation experiments.[3] As a driver for hydrodynamic experiments, the Marx bank, configured for 240 kV operation, will be directly connected to the imploding load and provide about 45 MA in 4 to 5 μs. When used for radiation experiments, the Marx bank will drive a radiating Z-pinch. For this purpose, the output current rise time must be much shorter (≈ 400 ns) than for hydro experiments because of load stability issues. An inductive-store/opening-switch configuration that is compatible with the Atlas hydro-driver design is being considered to provide the fast current risetime for the radiation load. The mainline approach is to use a plasma flow switch[4,5] with the Marx configured for 480-kV operation.

In this note, we analyze design options for implementing two alternate opening switch concepts on the Atlas generator: a fuse[6] and a plasma opening switch[7] (POS). Transmission line circuit models of Atlas have been developed that include physics-based electrical models for the fuse, POS, and Z-pinch load. The NRL transmission line code BERTHA[8] is used to calculate Atlas performance with the various design options. This is a preliminary study. None of the design options presented here is complete. Our goal is to provide a starting point from which these options can be pursued further. Moreover, at the time of this study, the Atlas circuit was still evolving and changes in this circuit will impact the results of the work reported here.

ENERGY TRANSFER TO IMPLODING LOADS WITH AN INDUCTIVE SYSTEM

The fundamental concepts of using inductive-storage/opening-switch systems to implode Z-pinches are not new and were first discussed formally by Reinovsky, et al.[9] Typically, a capacitor bank is discharged to ground through an inductor, L_0, and an opening switch, transferring the energy stored electrostatically to energy stored inductively. In practice, during this process a portion of the capacitor energy is dissipated in fault-protection and other current-limiting resistors, as well as in the opening switch. At the appropriate time, i.e., at or near peak current in L_0, the resistance of the opening switch increases and current is transferred to an output inductance, L_1, that comprises a coupling inductance and the initial inductance of the Z-pinch load.. The Z-pinch then collapses in a time $t = T_{imp}$ as a result of the JxB force associated with the current flowing through it. If the change of inductance of the Z pinch is $\Delta L(t)$, where $\Delta L(0) = 0$ and $\Delta L(T_{imp}) = \Delta L$, then for the simplified case described above and for fixed values of L_1 and ΔL, the kinetic energy of the Z pinch is maximum when[9]

$$L_0^2 = L_1^2 + L_1 \Delta L .$$

The kinetic energy is then converted into radiation. The above expression provides a starting point for selecting the optimum value of L_0. The value of L_1 should also be minimized for coupling the maximum energy to the load.[9]

0-7803-4214-3/97/$10.00 © 1997 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1997	**N/A**	**-**

4. TITLE AND SUBTITLE
System Study For A Possible Atlas Radiation Option

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Pulsed Power Physics BranclL Plasma Physics Division Naval Resemch Laboratory, Washington, DC 20375

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**7**	

ATLAS WITH FUSES AND Z-PINCH LOAD

An early design of the Atlas generator was modified to incorporate a fused opening switch coupled to a Z-pinch load with a self-triggered flashover closing switch as shown in Fig. 1. In this early design, current from the Marx bank operating at 240 kV (not shown in this figure) is delivered to the parallel-plate feed through multiple parallel cables connected to the cable headers. The closing switch is necessary during the conduction phase to prevent premature current flow to the load resulting from the resistive voltage developed across the fuse. Also, this premature load current inhibits the fuse from reaching the desired resistance for switching. Because of the higher voltages involved with the faster current rise times required for a Z-pinch load, the gap between the conducting plates in the region of the vacuum insulator was increased (from the hydro-mode value) to 5.1 cm (2 in). The vacuum insulator was also moved out to a radius of 65 cm to: (1) lower the inductance and (2) shield the insulator surface from unwanted UV radiation from the load. The gap in the conical vacuum transmission line section is 1.3 cm and the radial gap of the 4.3-cm long straight coaxial section (with an inner radius of 8.9 cm) just before the load is 1.9 cm. The load is 2-cm long with an initial radius of 5 cm and we assume a 10:1 compression ratio (ΔL = 9.2 nH). The inner edge of the fuse package is at a radius of 234 cm. The length of the flashover switch was set to 50 cm. The fuse package and closing switch design are based on those developed for the Shiva-Star generator[9,10] at the Air Force Research Laboratory (formerly the Air Force Weapons Laboratory). This design was also used for a short experimental series on Pegasus.

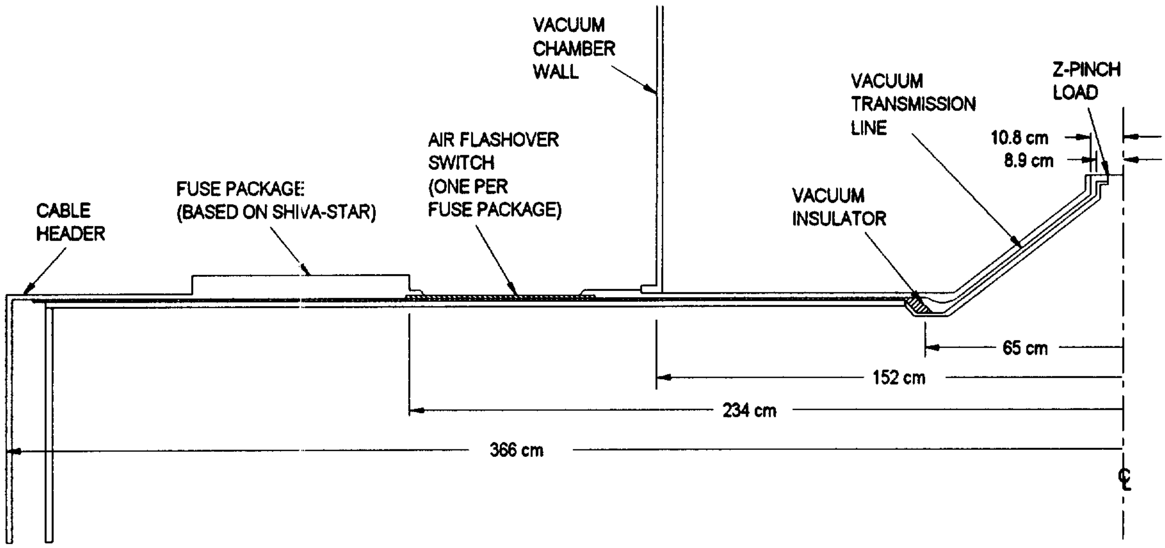

Fig. 1. Modified Atlas central region with a fuse and radiating Z-pinch load.

Our fuse model is based on the published[9] fuse resistivity vs. energy density for folded, 1-mil thick aluminum fuses quenched with 100-μm glass beads. Fuse dimensions are selected so that the maximum final energy density in the fuse is equal to 40 kJ/cm^3. Typically, the cross sectional area of the fuse is adjusted to conduct the required current up to the opening time (fuse "action") and the length is adjusted to obtain the optimum fuse energy density. Operating at a higher final fuse energy density than 40 kJ/cm^3 will turn the fuse into a plasma and cause the fuse to short out, which would terminate the transfer of energy to the load. If the final energy density is less than this value, transfer efficiency will be decreased because of the smaller opened resistance of the fuse. The Atlas fuse conduction time, T_{COND}, is increased by a factor of 2 over that for the Shiva-Star fuse. The other Atlas fuse parameters (conduction current, fuse length and width) are $\leq$ 50% extrapolations from Shiva Star. Before opening, the fuse must first dissipate energy in changing from a solid to a liquid to a vapor. This is energy lost from the system, above and beyond what is required by flux conservation.

The equivalent circuit in Fig. 2 is used to model the Atlas generator with a fuse and Z-pinch load. The value of the fuse inductance, which includes the inductance of the parallel plate feed between the cable header and the fuse (1 nH), is selected to provide maximum kinetic energy (a broad maximum) to the imploding load.[9] In most cases this optimum inductance is larger than what is actually required for this section of the generator. As an example, the 12.4 nH fuse inductance shown in Fig. 2, is about 7.6 nH more than is actually required for the fuse package.

The remaining circuit parameters were calculated from the design shown in Fig. 1. The inductance of the closing switch is based on an insulation thickness of 2 cm and a radial length of 50 cm. For this work, this switch was instantaneously closed when the fuse voltage reached 0.25 MV. Insulation thickness of 1.0 cm was assumed for the parallel-plate radial feed sections between the closing switch and the vacuum insulator. The total downstream inductance between the fuse and the load (including the initial inductance of the load) is 14.9 nH.

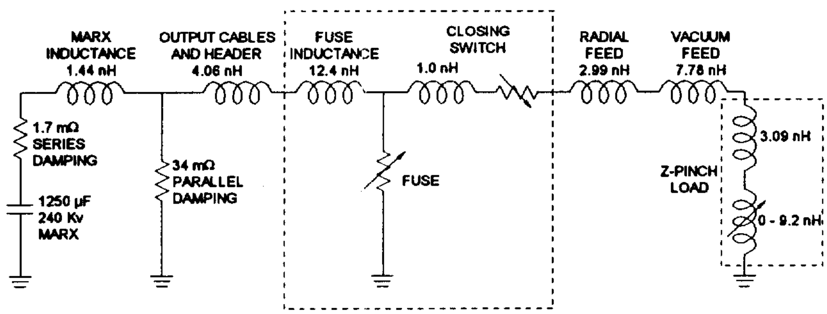

Fig. 2. Equivalent circuit used to model the Atlas generator with a fuse and Z-pinch load.

Results of the modeling of the circuit in Fig. 2 are plotted in Fig. 3. Upstream currents are plotted for both the case with a short at the fuse and with a fuse that opens at an optimum current for this circuit configuration. Maximum current into a short circuit across the fuse is about 43 MA, and a peak current of 37 MA is obtained with the fuse in place. For this simulation the fuse length and cross-sectional area were 107 cm and 2 cm^2, respectively. It was found that although the shape and amplitude of the load current was not very sensitive to fuse conduction time, the timing for the data in Fig. 3 provided the best combination of load current rise time and amplitude. Details of the Z-pinch and fuse voltage waveforms are also shown in the figure. The voltage at the fuse reaches 0.9 MV during fuse opening and the maximum current into the load during implosion is 14 MA. Peak kinetic energy of the 2-cm long imploding load is 0.74 MJ. The reason for the low value of load current is a combination of the effects of inductor-to-inductor transfer[9] and the large loss through the fuse after opening. At the time of peak load current, the current loss in the fuse is 40% of the total available upstream current.

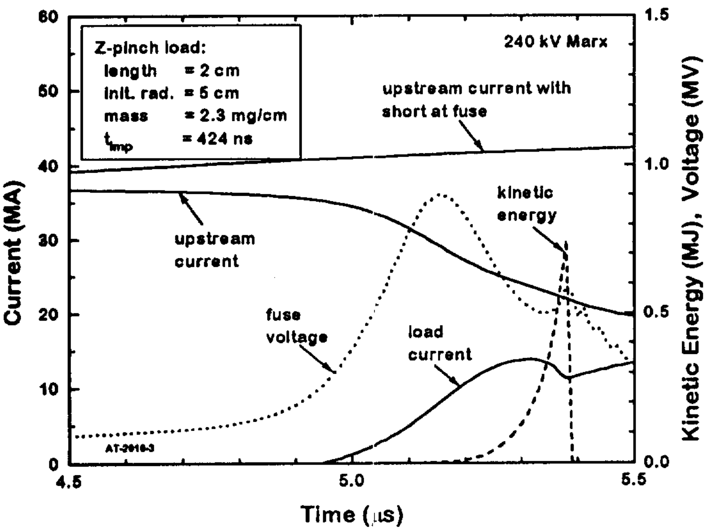

Fig. 3. Calculated waveforms with fuse and radiating Z-pinch load.

The peak voltage of 0.9 MV at the fuse will stress the 1-cm thick insulation downstream of the closing switch to ≈850 kV/cm, about 40% higher than the design criteria of 600 kV/cm. This may have to be reduced by closing the flashover switch at a lower voltage, increasing the downstream current rise time and lowering the voltage across the fuse. Because of the relatively insensitivity of the upstream inductance on Z-pinch performance as discussed above, the upstream insulation thickness can be large enough to accommodate the required voltages.

Details of the energy distribution are listed in Table I. At the time of implosion (time of 10:1 radius compression) 9.0 MJ is still in the capacitors, 4.5 MJ is in the inductance upstream of the fuse, 11.3 MJ is lost in damping resistors, 9.0 MJ total was dissipated in the fuse, 1.6 MJ is in the inductance downstream of the fuse, including the final inductance of the load, and the load has 0.74 MJ of kinetic energy. The 3.8 MJ dissipated by the fuse during the conduction phase represents about 42% of the total energy dissipated by the fuse, i.e., the energy dissipated during the conduction phase plus the energy loss required to conserve flux during the opening.

The kinetic energy delivered to the load is strongly dependent on ΔL and L_1.[9] The ΔL is fixed by the required 2-cm length and the typical 10 to 1 compression ratio. Modeling runs were also made using one-half of the baseline value of L_1, or 7.4 nH. Of course, whether this reduction in inductance could ever be accomplished in a

Table I. Energy distribution with fuse and Z-pinch load.

	At fuse opening (MJ)	At Z-pinch implosion (MJ)
Marx bank (stored)	10.6	8.96
Series resistors (dissipated)	7.33	8.07
Parallel resistors (dissipated)	3.09	3.26
Upstream inductance (stored)	11.2	4.50
Fuse (dissipated)	3.79	9.04
Downstream inductance (stored)	0	1.57
Load kinetic energy	0	0.74
Total	36.0	36.14

real system still needs to be determined. The fuse inductance was also decreased to 5.6 nH from the previous 12.4 nH to provide the optimum total upstream inductance of 11.1 nH. This reduced inductance scenario increased the peak load current during implosion to 20 MA and peak kinetic energy to 1.3 MJ.

It would appear that the combined losses associated with inductor to inductor transfer, the extra energy required to vaporize a fuse, and the current loss in the fuse after opening will likely restrict the usefulness of fuses for the Atlas radiation option. Further development aimed at improved fuse performance, or possibly less restrictive assumptions regarding the location of the fuse, may mitigate this situation.

ATLAS WITH A POS AND Z-PINCH LOAD

We have also investigated the option of using a POS to produce the required current rise time for a Z-pinch load. A POS could offer several advantages over a fused system by (1) practically eliminating the resistive losses during the conduction time of the switch (although there will be some loss from MHD-induced motion of the POS), and (2) allowing closer placement of the switch to the load, thus reducing the downstream inductance and providing a more favorable inductance distribution.

On the other hand, a POS has never been operated at current levels and conduction times comparable to those that would be required for Atlas. The ACE4 generator has operated at 5 MA with about 1-μs conduction time.[11] To minimize the extrapolation from these operating parameters, we would want to configure Atlas to give the maximum current in the shortest time to the POS. Thus, the 480-kV configuration of the Atlas Marx banks would be preferable, with a time to peak current of a little less than 3 μs. The physics of the POS conduction on the 1-μs time scale is well known.[7,12] The POS in the opened state can be characterized as a gap of several mm.[7] The processes governing the gap growth and final size are still under investigation.[7,13] In what follows, conduction and opening physics will be assumed to scale to the plasma density required for the Atlas current level and conduction time.

The drawing of the Atlas generator with a POS is shown in Fig. 4. Based on scaling considerations[12] for an

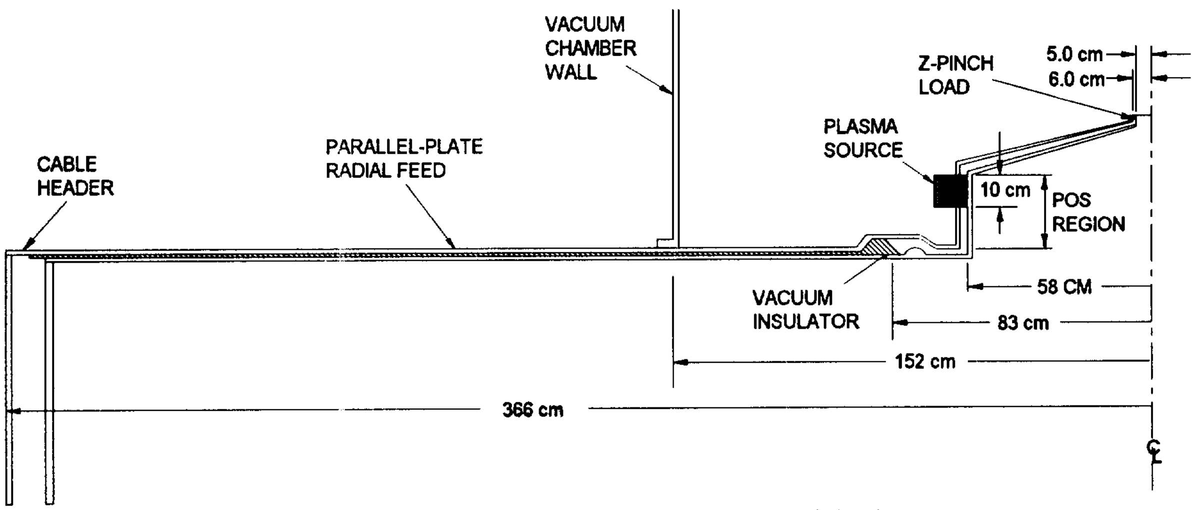

Fig. 4. Atlas with a POS and radiating Z-pinch load.

assumed 2-μs conduction time, we made a rough estimate for preliminary POS parameters for Atlas. This resulted in a POS cathode radius of 58 cm and POS-plasma fill length of 10 cm. As discussed below, with a doubly-ionized carbon plasma of electron density $n_e \approx 5.5\times10^{17}\mathrm{cm}^{-3}$, these dimensions are consistent with the upstream edge of the

POS plasma being displaced a distance equal to the POS-plasma length during the conduction phase. For comparison, successful POS opening was demonstrated[11] at the 5-MA, 1-μs level on ACE4 with a 20-cm radius, a 12- to 20-cm length, and $n_e \approx 10^{16}cm^{-3}$. The vacuum insulator in Fig. 4 is now located at an 83-cm radius (vs. the 65-cm position for the fuse circuit) to accommodate the POS. The vacuum gap in the POS region is 2.5 cm with the gaps in the conical feed to the load tapering from 2.5 to 1 cm at the load end. The radial gap at the Z-pinch load is 1 cm.

The electrical circuit model for the POS option is shown in Fig. 5. To convert the Marx parameters from 240 to 480 kV operation, the Marx capacitance decreases by a factor of 4 and the Marx inductance and damping resistors (see summary) increase by the same factor. The inductance of the output cables and cable header was not changed, assuming that the same number of cables would be used for both voltages. The rest of the circuit elements were calculated based on the dimensions shown in Fig. 4 and described in the previous paragraph.

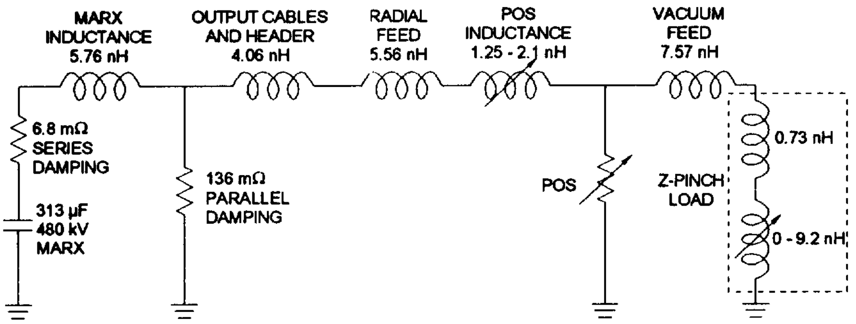

Fig. 5. Equivalent circuit used to model the Atlas generator with a POS and Z-pinch load.

The total upstream inductance for this circuit at the time of POS opening (including the inductance of the POS region, see next paragraph) is 17.5 nH and the downstream inductance, including the initial load inductance, is 8.3 nH. The upstream inductance (L_0) is now larger than the ideal optimum of 12.1 nH because of the higher inductance of the 480-kV Marx bank and the fact that the POS is closer to the load. However the load kinetic energy has a broad maximum about the optimum upstream inductance and modeling runs have shown little or no increase in load energy when that inductance is arbitrarily reduced to the optimum value.

The standard NRL Z_{flow} POS model[14] was used to simulate the opening of the switch along with an additional calculation to approximately account for the movement of the plasma in the POS region during the conduction time of the POS.[15] We assumed a "snowplow" model applied to the annular POS plasma at the POS cathode to calculate an effective figure-of-merit for the rate at which the inductance changes in the POS region during the conduction phase. As noted in Fig. 5 the inductance in the POS region increases from 1.25 to 2.1 nH during the conduction time to account for the plasma motion in the POS region. When the snowplow reaches the end of the plasma fill region, the switch opens according to an assumed $Z_{flow}(t)$ model. Based on analyses of ACE4 data,[16] we used a Z_{flow} that rises linearly from zero to 0.1 Ω in 100 ns. This corresponds to a POS gap of about 2 mm. Of course, the assumed Z_{flow} behavior must be demonstrated at the Atlas parameters (conduction time, conduction current, and POS radius). This POS model partitions the total load current into cathode current and vacuum flow. Only the cathode current is used as load current (current flowing in the Z-pinch) in the calculation.

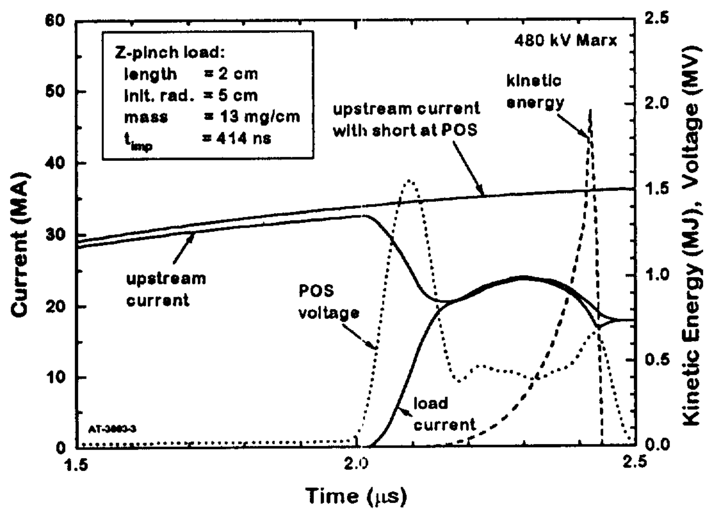

Fig. 6. Calculated waveforms with POS and radiating Z-pinch load.

Results of the modeling of the circuit in Fig. 5 are plotted in Fig. 6 for the POS/Z-pinch-based Atlas design. The short circuit current shown in the figure is calculated with the short at the upstream end of the plasma fill region. The difference between this current and the current with a POS, prior to switch opening, results from the increasing inductance in the POS region associated with the plasma motion described above. A doubly ionized carbon plasma with an electron density of $n_e = 5.5 \times 10^{17}$ cm^{-3} provides the proper conduction time (this density is a factor of ≈ 10 higher than what has been used to date in POS experiments[17]). Peak POS current just prior to opening is 32.5 MA compared with about 37 MA for the baseline fuse case. Peak kinetic energy is 1.96 MJ with a peak load current of 23.5 MA compared with 0.74 MJ and 14 MA, respectively, for the baseline fuse case. Peak voltage at the POS is 1.6 MV. Note the current loss during the implosion that was present with the fuse is absent here. There is some loss, however, at the time of implosion. The ion current loss in the POS region is assumed to be negligible, as is the case in previous experiments. However, the issue of ion-current loss for the POS is still under investigation.

A summary of the energy distribution in the Atlas generator with a POS is shown in Table II. Note that when using a POS, relatively little energy (0.3 MJ) is lost during the conduction phase - unlike the fuse where almost 4 MJ was lost before opening. On the other hand, more energy is left in the capacitor bank with the POS, partly due to the early (2 μs) opening time.

Table II. Energy distribution with POS and Z-pinch load.

	At POS opening (MJ)	At Z-pinch implosion (MJ)
Marx bank (stored)	18.58	15.09
Series resistors (dissipated)	7.25	9.27
Parallel resistors (dissipated)	0.64	1.14
Upstream inductance (stored)	9.35	3.36
POS (plasma motion)	0.30	0.30
POS (loss)	0	2.66
Downstream inductance (stored)	0	2.44
Load kinetic energy	0	1.96
Total	36.12	36.22

Peak voltages of 1 MV are predicted at the downstream end of the radial feed region (just upstream of the vacuum insulator, see Fig. 4). The 1-cm insulation there will have to be increased to withstand the voltage stress induced by the opening switch. The resultant impact on the Z-pinch performance will have to be evaluated. For example, one could grade the insulation thickness from the vacuum interface back toward the Marx to minimize this problem. Various tradeoffs to optimize the POS design were not explored.

SUMMARY AND CONCLUSIONS

Detailed circuit analyses have been made for the Atlas generator with opening switches driving a Z-pinch load. Both fuses and a POS have been considered as possible candidates for the switch. These analyses have determined that about 0.74 MJ of kinetic energy will delivered to a Z-pinch load with a fuse as the opening switch. If circuit inductances could be reduced by a factor of 2 from the base line design, the energy would increase to 1.3 MJ. The major losses result from inductor to inductor transfer and resistive losses in the fuse during both the fuse conduction time and during the time of Z-pinch implosion. Using a POS as the opening switch with a 480-kV Marx configuration, nearly 2 MJ could be delivered to the load. Scaling the POS to Atlas is uncertain. The results presented here used preliminary circuit parameters for the Atlas generator based on initial estimates by LANL. Our analysis also show that the circuit used for the 480-kV case provides more damping than the 240-kV circuit, resulting in less inductive energy available at the end of the POS conduction phase than might be expected.

ACKNOWLEDGMENTS

The authors would like to acknowledge useful discussions with and the help of Bill Reass, Jack Schlacter, and J. Cochrane at LANL, and P. Ottinger, G. Cooperstein, and D. Mosher of the Pulsed Power Physics Branch at NRL.

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